

**Executive Summary of
Accelerator Improvements to Support Run II Goals**

December 13, 2002

At the Department of Energy Review Fermilab presented the following goals in luminosity delivered per detector by the end of FY 2008(FY 2010):

Base goal: $6.5(10)\text{fb}^{-1}$

Stretch goal: $11(17)\text{fb}^{-1}$

These compare to a total of 0.14fb^{-1} delivered in Run I, with which the top quark was discovered.

The base goal represents what could be expected if the majority of accelerator improvements envisioned perform as planned, while the stretch goal indicates what could be expected if essentially everything that is envisioned is successful.

The detailed plan for FY 2003 addresses the limitations that need to be overcome to raise performance by the end of the year into the range $6\text{--}8 \times 10^{31}\text{cm}^{-2}\text{sec}^{-1}$, which corresponds to about $0.4\text{--}0.6\text{fb}^{-1}$ of accumulated luminosity per year. Some of these limitations have relatively straightforward and well-understood hardware solutions, but in most cases we are working to identify the underlying mechanisms and then to develop solutions.

The strategy for increasing luminosity beyond the level of about 0.5fb^{-1} per year is based primarily on increasing the number of antiprotons in the Tevatron. The technical elements needed to do this over the period FY 2004-2006 are included in a document written in December, 2001. The stretch goal is to reach the ability to deliver 3.0fb^{-1} per year by the end of FY 2006; the base goal is to reach 1.8fb^{-1} per year by then.

The long-term plan includes the strategy for addressing the major risk factors in achieving the long-term stretch scenario, which fall into four major categories:

- Operational reliability
- Technical success in major R&D initiatives
- Proton economics
- Resources (people and funding)

Funding this plan requires an increase in the laboratory budget from \$286 M in FY 2003 to \$309 M in FY 2004, \$321 M in FY 2005, and \$334 M in FY 2006. The figures for FY 2004 and beyond are at the same level as Fermilab's FY 2002 budget, correcting for 4% inflation. After the massive redirection of effort within the laboratory to support the Run II effort on this year's budget, there is no potential to move additional resources from the rest of the laboratory next year and still meet commitments to ongoing projects.

The identified technical improvements and modifications contained in the ambitious plan described in this document should support a peak luminosity in the range $2\text{--}4 \times 10^{32}\text{cm}^{-2}\text{sec}^{-1}$. To integrate luminosity faster than allowed by this plan would require currently unidentified technical breakthroughs.

The ongoing Run II effort is being organized, and will be managed, as a project within the Beams Division. This means the effort will incorporate project-like organization, work organized and budgeted using a Work Breakdown Structure, resource-loaded scheduling with accompanying milestones, and periodic reporting. A detailed plan for the period FY 2004-2006 is expected to be completed by June 1, 2003. The plan for the later years will be at a different level of detail and will allow the flexibility needed to respond to what is learned in earlier years.

Accelerator Improvements to Support Run II Goals

December 13, 2002

This document presents a preliminary overview of the performance that could be achieved, and the resources that will be required, within a program whose goal is to maximize output of the Tevatron Collider during the period leading up to the initiation of physics results from the Large Hadron Collider at CERN. It is based in part on information presented at the October 28-31, 2002, Department of Energy Review of Run II and in the document "Plans for Tevatron Run IIB" released in December 2001. A more complete plan is in preparation and will be presented, as requested by the DOE, by June 1, 2003.

Goals

At the Department of Energy Review Fermilab presented the following goals in luminosity delivered per detector by the end of FY 2008(FY 2010):

Base goal: $6.5(10)\text{fb}^{-1}$

Stretch goal: $11(17)\text{fb}^{-1}$

The relatively large (factor of two) spread in the goals reflects the difficulty of projecting a performance improvement of a factor of ten when such an improvement relies heavily on components that are still in an R&D phase. The base goal represents what could be expected if the majority of accelerator improvements envisioned perform as planned, while the stretch goal indicates what could be expected if essentially everything that is envisioned is successful (technically and in terms of schedule). The DOE Review committee regarded the base goal as "a significant challenge" in and of itself, and the stretch goal as "very uncertain". The committee recognized that uncertainties exist in association with the R&D programs supporting a wide range of accelerator upgrades, the accelerator physics issues that may be encountered as the luminosity is pushed a factor of ten beyond current performance (and a factor of several hundred beyond the original design of the Tevatron), and the availability of human and fiscal resources.

In both the base and stretch scenarios an evolutionary reconfiguration of the accelerator complex is envisioned over the period FY 2003-FY 2006. During this period the accelerator complex is being asked to support simultaneously operations for integrating luminosity, machine studies aimed at providing the underpinnings of a campaign of continuous improvement, shutdowns for implementation of upgrades and maintenance of existing equipment, and the development and delivery of proton beams at average intensities about a factor of five beyond current experience in support of the Fermilab neutrino program. Taken together, these goals are as ambitious as any Fermilab has undertaken in the past.

Assuming success in the above endeavors, Fermilab would have a capability to integrate between 1.8fb^{-1} (base) and 3.0fb^{-1} (stretch) per year by the end of 2008, allowing 15fb^{-1} to be achieved by 2010 in the stretch scenario. Advancing beyond this would require the development of new strategic elements beyond those outlined in the plan below. What it might take to do this is discussed briefly at the end of this document.

Current Performance

At present the Tevatron is operating with an average luminosity of about $3 \times 10^{31} \text{cm}^{-2} \text{sec}^{-1}$, supporting the integration of roughly $5 \text{ pb}^{-1}/\text{week}$. This level of performance is about a factor of four higher than on January 1, 2002, but below what had been anticipated. The present luminosity is about a factor of two beyond that routinely obtained in the previous collider run (Run I), and a factor of thirty beyond the original design goal of the Tevatron ($1 \times 10^{30} \text{cm}^{-2} \text{sec}^{-1}$).

Present limitations that need to be overcome to raise performance into the $6\text{--}8 \times 10^{31} \text{cm}^{-2} \text{sec}^{-1}$ range include:

- Raising the antiproton production rate to $18 \times 10^{10}/\text{hour}$.
- Reducing antiproton emittance dilution on the Main Injector to Tevatron transfer.
- Diagnosing and eliminating antiproton emittance growth, and proton and antiproton beam loss, on the Tevatron acceleration ramp.
- Diagnosing and improving the 150 GeV proton lifetime in the Tevatron.
- Improving proton and antiproton emittance preservation on all transfers within the accelerator complex.

The plan for FY 2003 addresses all of these issues. Some have relatively straightforward and well-understood hardware solutions, but in most cases we are working to identify the underlying mechanisms and then to develop solutions. Improved diagnostics are required to do this in many cases. The FY 2003 “stretch” goals assume success in all these endeavors; the FY 2003 “base” goals assume success in the majority. In parallel the FY 2003 plan includes integration of the Recycler into operations near the end of the year.

The Strategy for Increasing Luminosity

Fermilab believes that after resolution of the issues above the current accelerator configuration will support a luminosity in the range $6\text{--}8 \times 10^{31} \text{cm}^{-2} \text{sec}^{-1}$ ($0.45\text{--}0.6 \text{ fb}^{-1}/\text{year}$ with 40 weeks of operation annually). The technical elements for going beyond this have been defined for some time, and are collected in the document “Plans for Tevatron Run IIB” issued in December, 2001 (and available at <http://www-bd.fnal.gov/doereview02/RunIIBTDR.pdf>). The strategy is shown schematically on the following timeline:

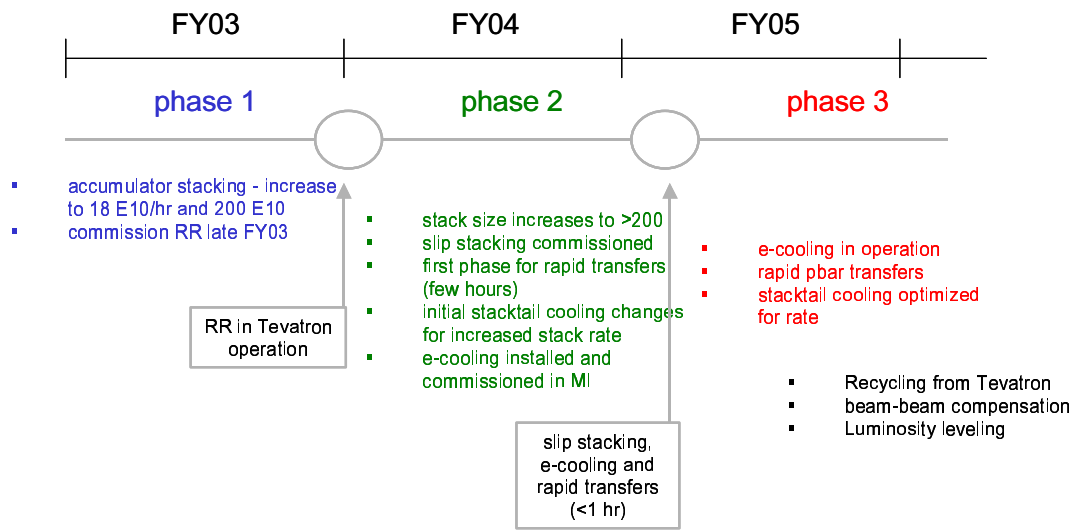


Figure 1: Timeline showing implementation of accelerator improvements expected to lead to a luminosity performance in the range $2-4 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

The timeline displays a **strategy based primarily on increasing the luminosity by increasing the number of antiprotons in the Tevatron**. The ability to increase further the number of protons is limited by the forces experienced by the antiproton beam as a result of the electromagnetic fields generated by the higher intensity proton beam (the “beam-beam” effect).

The resulting approach to bringing the luminosity up has four primary technical components:

- More protons on the antiproton production target
Proton accumulation in the Main Injector
- Increased antiproton yield per proton on target
Lithium lens upgrade
AP-2 aperture improvements
- Increased antiproton stacking ability
Accumulator stochastic cooling improvements
Electron cooling in the Recycler
- Beam dynamics in the Tevatron
Electron lens based beam-beam compensation

Significantly improved beam diagnostics and beam simulations will be required to support these improvements. No major (accelerator) shutdowns beyond approximately six weeks are required to support this plan.

Assuming success in all these endeavors, the following performance could be expected as the strategy is executed:

Parameter	Now	Completion of		
		Phase 1	Phase 2	Phase 3
Protons/bunch	17.0	27.0	27.0	27.0 $\times 10^9$
Antiprotons/bunch	2.4	3.0	4.9	14.8 $\times 10^9$
Bunches	36	36	36	36
Antiproton Production	11.5	18	28	45 $\times 10^9$ /hour
Luminosity	30	80	130	390 $\times 10^{30} \text{cm}^{-2} \text{s}^{-1}$
Luminosity/week	5	15	25	88 pb^{-1} /week

Table 1: Parameter evolution in the stretch scenario.

Merging Table 1 and Figure 1 generates the following evolution of integrated luminosity if everything succeeds (stretch scenario):

End of	Luminosity per year	Integrated Luminosity Total	
FY02	.08	.08	fb^{-1}
FY03	.32	0.4	fb^{-1}
FY04	.60	1.0	fb^{-1}
FY05	1.5	2.5	fb^{-1}
FY06	2.5	5.0	fb^{-1}
FY07	3.0	8.0	fb^{-1}
FY08	3.0	11.0	fb^{-1}

Table 2: Luminosity evolution in the “stretch” scenario

The Strategy for Increasing Luminosity: Uncertainties and Risks

Major risk factors in achieving the stretch scenario fall in four major categories:

- Operational reliability
- Technical success in major R&D initiatives
- Proton economics
- Resources (people and funding)

Operational reliability

The Tevatron complex consists of elements that will be nearing 40 years of age in the year 2010. The Tevatron itself will be 27 years old in 2010. The complex currently achieves about 90 hours per week of luminosity plus studies. This pace cannot be maintained over the next eight years without a significant investment in maintenance and infrastructure initiatives.

A study completed over the summer of 2002 identified major operational vulnerabilities within the accelerator complex. Items with the potential to interrupt Tevatron operations for more than three months were identified. Those items that are deemed to have significant risk are identified below along with cost (materials & services only) to mitigate the associated risk:

Area	Component	Cost
Linac	7835 Amplifier Tubes	\$1.5M
Linac	F1123 Switch Tubes	\$200K
Linac	New Quadrupole Power Supplies	\$1.0M
Linac	Water System Rebuild	\$500K
Booster	Orbit Bump Magnets	\$1M
Booster	Low Level RF	\$100k
Booster	High Power RF	\$7.5M
Booster	RF Accelerating Cavities	\$10M
Main Injector & Beamlines	Dipole PS Transformers	\$150k
Main Injector & Beamlines	Quad PS Transformers	\$80k
Main Injector	Kicker Magnet Vacuum Tubes	\$500k
Tevatron Low Beta	PS Magnetics	\$30k
Tevatron Cryogenics	Centrifugal Cold Compressors	\$100k
Site Infrastructure	345-KV Switchgear KRS	\$200k
Site Infrastructure	345-KV Switchgear MSS	\$300k
Site Infrastructure	345-KV MSS Transformer	\$1.2M
Site Infrastructure	Harmonic Filter Damping Resistors	\$20k

Table 3: Major vulnerabilities with an associated risk for significant interruption of Run II operations over the period 2002-2008.

The elements in the table add up to \$24M, with the single largest components being associated with the Linac and Booster (our two oldest machines). The Linac is particularly problematic in that we currently project about five years of remaining useful life unless an initiative is undertaken to address issues related to tube availability, power supply, and water systems. The Booster has several vulnerabilities, the most significant of which requires a new RF system (see proton economics discussion below). The vulnerability study is continuing with an expectation that the exposure in terms of dollars could grow by 30% once everything has been unearthed.

Technical Success in Major R&D Elements

Major technical risks among the elements of the upgrade program include:

- More protons on the antiproton target
Stability of 40 dB of loop gain in RF feedback beamloading compensation as required for slip-stacking in the Main Injector. (not yet demonstrated anywhere.)
- Increase antiproton yield per proton on target
Lithium lens lifetime vs. gradient vs. production rate
- Increased antiproton stacking ability
Stability of the Accumulator stochastic cooling system
Electron cooling in the Recycler: electron beam stability/operational environment
- Beam dynamics in the Tevatron
Beam lifetime
Dynamics in a strong-strong regime (antiproton intensities approaching protons)
- Antiproton Recycling
Can it be made to work operationally?

The “base goals” are robust against shortfalls in a few of these areas; the “stretch goals” are not. However, several elements, most notably a functional Recycler with electron cooling are required to work to achieve the base goal.

Proton Economics

The Fermilab 8 GeV Booster is required to provide protons to the Main Injector for antiproton production, to the MiniBoone short baseline neutrino experiment, and, starting in 2005, to the NuMI/MINOS long baseline neutrino program. The planned performance of the Booster, while consistent with simultaneous operations of Run II and the neutrino program, is not consistent with increased proton fluxes on the antiproton production and/or neutrino production targets. In other words providing more protons on the antiproton production target, a key component of the long- range Run II plan, will require an increase in the number of Booster cycles that can be run per hour.

The impediments to raising the number of pulses per hour are beam loss within the Booster leading to radiation on the surface and activation of components in the Booster enclosure. The latter is the more serious problem at present and likely to remain so throughout the next few years. Booster losses are currently administratively controlled at 1W/m. Experience has shown this to be about the maximum level that allows ready access for maintenance activities.

The most straightforward approach to increasing the number of pulses per hour would be to replace the 18 Booster RF cavities with wider aperture models. This helps in two ways: first the RF cavities represent significant aperture restrictions, hence they tend to become very activated; and second, the RF cavities are the highest routine maintenance items in the machine. Their replacement would mitigate the losses and improve the ability to maintain the accelerator. The cost of a complete set of wide aperture cavities and their associated support systems is \$15-20M. A prototype is expected to be installed in 2003.

The replacement of the Booster with a modern rapid cycling proton synchrotron, while very attractive for the long term program in neutrino physics that is on the road map described in the recent HEPAP subpanel report, is more costly (several \times \$100M) and would be difficult to implement without a significant interruption to collider operations or in time to have a significant impact on Run II luminosity.

Resources (People and Funding)

The Beams Division estimates that approximately 20 people, beyond the current staffing level, are required to support the plan outlined above.

Summarizing the above discussions, needs beyond inflation (materials & services + labor, direct costs only) over the period FY 2003-2006 include:

- Support of ongoing operations (increment to current budget) \$16M
- Maintenance/Reliability initiatives (increment to current budget) \$30M
- R&D and implementation of technical upgrades (total need) \$25M

Of this amount, approximately \$7.5M is included in the FY 2003 budget. So assuming this as a base, the estimated need is \$41M, plus inflation on the base budget, as an increment required to implement the items listed above over the period FY 2003-2006. A better estimate of these needs will be developed as part of the long-range plan to be presented in June 2003. However it is believed that the present estimate is probably accurate to $\pm 20\%$.

Funding this plan requires an increase in the laboratory budget from \$286 M in FY 2003 to \$309 M in FY 2004, \$321 M in FY 2005, and \$334 M in FY 2006. The figures for FY 2004 and beyond are at the same level as Fermilab's FY 2002 budget, correcting for 4% inflation. After the massive redirection of effort within the laboratory to support the Run II effort on this year's budget, there is no potential to move additional resources from the rest of the laboratory next year and still meet commitments to ongoing projects. The funding profile for the laboratory listed above would make it possible to invest \$14 M per year more in the accelerator effort than this year, adding up to the required \$41 M over the three-year period.

Beyond the Current Plan

The elements of the plan outlined above, in particular the identified technical improvements and modifications to support a luminosity in the range $2-4 \times 10^{32} \text{cm}^{-2} \text{sec}^{-1}$, has remained static over the last few years. Moving beyond this plan, in particular to reach 15fb^{-1} as early as 2008, would require currently unidentified technical breakthroughs. Given the current understanding of the Tevatron there are few opportunities for such breakthroughs, although if one were to come it would most likely come in a very few areas:

1. Increasing the number of antiprotons

At the end of Phase 3 of the Run II plan the antiproton intensity is 55% of the proton intensity. This is to be compared to 10-15% today. There are severe impediments to improving the antiproton intensity further, in the areas of antiproton production, antiproton storage, and the beam dynamics related to beam-beam interactions in a completely strong-strong regime.

2. Making the beam smaller in collisions.

The luminosity can be increased by lowering the cross-sectional areas of the beams in collision. Lowering the beam size itself can be achieved either by lowering the beam emittance or by modifying the optics of the interaction region to create smaller beams for the same emittance. Lowering the beam emittance requires an enhanced cooling mechanism. The most attractive would be either electron or stochastic cooling in the Tevatron. Both such systems are well beyond state-of-the-art at the moment and so would require crash R&D programs to bring into a state of reality. Lowering the beam emittance has the undesirable effect of increasing the head-on beam-beam tune shift. Whether this could be tolerated would require significant accelerator physics study and analysis.

Modifying the optics to create smaller beams in collision (lowering " β^* ") has the advantage that it does not increase the beam-beam tune shift experienced by the antiprotons. The downside is that taking advantage of the lower β^* requires shortening the bunches in the Tevatron (an optical depth-of-field effect). This would probably require a new, higher frequency, higher voltage, RF system for the Tevatron.

3. Improving the luminosity lifetime

One could imagine increasing the ratio of integrated luminosity to initial luminosity through a variety of manipulations including luminosity leveling or beam cooling. These are both special applications of the modification described above and hence subject to similar constraints.

Any additional improvements must satisfy some fundamental constraints: they cannot have significant negative impact on completing the upgrades already planned and they must be designed and built early enough to increase the integrated luminosity by 2008. Probably the most useful thing that could be done at the moment would be to organize a small workshop to explore options and see if anything looks potentially viable. We are planning such a workshop for January 2003.

Organization and Management of the Run II Accelerator Effort

The ongoing Run II effort is being organized, and will be managed, as a project within the Beams Division. This means the effort will incorporate project-like organization, work organized and budgeted using a Work Breakdown Structure, resource loaded scheduling with accompanying milestones, and periodic reporting.

Organization and Responsibilities

Run II is being organized as an integrated project within the Beams Division (BD). This organization will rely on support from the BD departments (as well as others) via a matrixed approach. Overall coordination and management will be provided by the BD with the execution provided by persons both within and outside the Beams Division. However, all resources (financial and human) will be allocated via the Run II Project.

The responsibility for the execution of the Run II Project resides with the Beams Division Head. He will be assisted by three project coordinators with responsibility for Operations, Reliability, and Accelerator Upgrades. The three project coordinators have been identified and will coincidentally hold the positions of BD Deputy Head, BD Associate Head for Engineering, and BD Assistant Division Head for Run II. These dual assignments will facilitate the integration of Run II within the BD. In addition the new Beams Division Head has been identified and will assume this position on January 15, 2003. A sub-project structure has been identified and sub-project managers are being identified and assigned.

Progress in developing and executing the plan will be monitored by a Project Management Group (PMG) under the auspices of the Fermilab Directorate. The Associate Director for Accelerators will chair the PMG. It is anticipated that the PMG will meet at least monthly with its first meeting in January 2003.

Work Organization

Work will be defined and organized utilizing a Work Breakdown Structure (WBS). The WBS for FY 2003 activities is completely developed and was presented at the October DOE Review of Run II. The WBS for the out-years is in the final stages of development and is being integrated into the BD budgeting/accounting system. The WBS for Run II will directly reflect the project organizational elements described above. This will allow the project and sub-project coordinators to control their work effectively.

The designs and specifications of the elements of the WBS will be described in a series of technical documents that will be prepared (initially) for the June 1, 2003 submission. Because of the R&D component of many of the elements of the Run II plan it is anticipated that these documents, and the WBS itself, will have to accommodate some flexibility as conditions change during execution of the plan. The laboratory will utilize the Accelerator Advisory Committee (AAC, a standing committee composed of outside accelerator experts) to review and comment on the technical elements of the Run II plan.

A resource-loaded schedule (RLS) directly tied to the WBS will be used to plan the work and to report progress against the plan. The RLS for FY 2003 was presented at the October DOE

Review. The WBS and RLS describing the period FY 2003-2006 are expected to be completed by June 1, 2003. Major milestones will be identified within the RLS for monitoring the progress of the effort. The RLS is expected to recognize major activities outside of Run II that nonetheless impact operations, e.g. operations of long and short baseline neutrino experiments and shutdowns for CDF and DZero upgrades.

Reporting

Periodic reports will be prepared. Reports are expected to cover technical, cost, and schedule performance relative to the plan. The Beams Division will track progress on a monthly basis and report to the PMG. A more formal report will be prepared on a quarterly basis.